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RELATIVE ABUNDANCE OF IRON-GROUP NUCLEI IN SOLAR COSMIC RAYS

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ABSTRACT

The abundance of the iron-group nuclei relative to oxygen in a solar cosmic-ray event has been determined for the first time in the event of September 2, 1966; it was found to be $(1.1 \pm 0.3) \times 10^{-2}$ above 24.5 MeV nucleon^{-1}. This ratio is consistent with the solar value determined spectroscopically but is over an order of magnitude smaller than the galactic cosmic-ray ratio. This result is in agreement with the concept already evolving from measurements on other nuclei that the relative abundances of solar cosmic rays reflect those of the solar photosphere for multicharged nuclei with approximately the same nuclear charge-to-mass ratio.

INTRODUCTION

Continued study of the nuclear-emulsion plates exposed aboard sounding rockets in the September 2, 1966, solar cosmic-ray event has led to a determination of the abundance of the iron-group nuclei relative to other nuclear species. This is the first event for which it has been possible to detect nuclei in this charge region. Previously the higher minimum detectable energy imposed by the thicker covering material, together with the steep energy spectra of solar particles, prevented the observation of these iron-group particles.

EXPERIMENTAL APPROACH

The nuclear-emulsion particle detectors used in this experiment are the same as those used in the measurements on the hydrogen, helium, medium (carbon, nitrogen, and oxygen), and neon nuclei in the September 2, 1966, event reported previously (Durgaprasad *et al.* 1968). The details of the experimental program and the general experimental procedure are described in that article and in papers referred to therein. The results to be reported here were obtained from the first of the three sounding-rocket flights, 8.7 hours after the solar flare on September 2, 1966.

The nuclear-emulsion particle tracks analyzed in this study were selected from those found in a scan for heavy nuclei in the central surface area of the emulsion pellicle. In order to avoid particles whose energies may have been significantly degraded by ionization energy loss in the atmosphere below, only tracks entering the emulsion from the upper hemisphere were accepted. A minimum projected length of 125 μ was demanded of all tracks, so that adequate measurements could be made. This length, together with the path length through the thin (0.023 g cm^{-2}) protective cover above the emulsion pellicle, gave a detector cutoff energy for iron nuclei typically about 24.5 MeV nucleon^{-1}. Charge identification was made from measurements of the integral number of delta rays (secondary electrons) as a function of residual range.

ANALYSIS

Figure 1 shows a histogram of the best estimate of the nuclear charge from delta-ray measurements on tracks in the very heavy scan along with the same measurements on

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a sample of about 500 particle tracks from other scans. A uniform delta-ray convection was used throughout. The unshaded portion of Figure 1 represents preliminary observations from an analysis still in progress, which are included only to show the resolution of the iron-group events from lower-charge events. The relatively large error in the charge determination in the region of the heavy nuclei results from a combination of the large variations in the particle charge-to-mass ratio in the high-charge region and from the difficulty of making accurate charge measurements on short tracks of heavy nuclei. Because of the lack of charge resolution, the flux that will be quoted will be for the iron group from charge 22 (Ti) to 30 (Zn), although the nature of the distribution and the knowledge of relative abundances in general suggest that the nuclei are predominantly those of iron.

In all, twenty-three events were found that satisfied the acceptance criteria and had measured charges of 22 or more. The detector area which was scanned was 33.9 cm^2; the solid angle was 1.08 sterad; and the collection time was 262 sec. The measured flux of iron-group nuclei is then $(24.0 \pm 5.0) \times 10^{-4}$ particle cm^{-2} $sterad^{-1}$ sec^{-1}, with an energy per nucleon above 24.5 MeV.

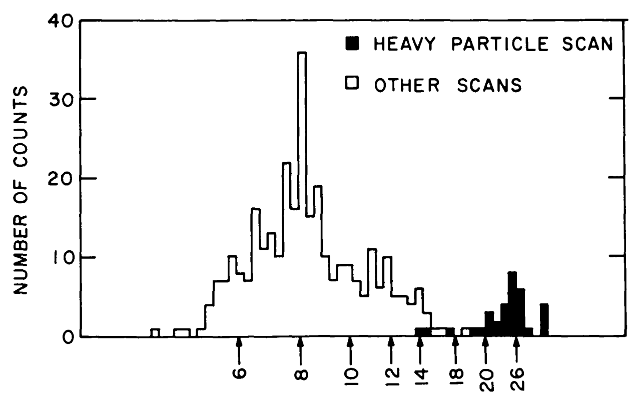

FIG. 1.—Distribution of observed charges above the same minimum range. Unshaded portion of graph represents tentative results from a smaller scanning area, with no attempt to obtain a high efficiency for detection below charge 8. The charge scale assignment was based on the present work and on a sample of tracks identified by Durgaprasad *et al.* (1968). Tracks in the shaded part of the histogram have superior statistics because of their higher delta-ray density.

The flux of oxygen nuclei with energies above 24.5 MeV $nucleon^{-1}$ determined previously (Durgaprasad *et al.* 1968) leads to an Fe/O value of $(1.1 \pm 0.3) \times 10^{-2}$ above the same energy per nucleon and hence the same velocity. Studies of this and previous events (Fichtel and Guss 1961; Biswas, Fichtel, and Guss 1962; Biswas *et al.* 1963; Biswas, Fichtel, and Guss 1966; Durgaprasad *et al.* 1968) have shown that the major groups of nuclei with the same nuclear charge-to-mass ratio have the same energy per nucleon flux spectra, and, above a given energy per nucleon, the relative abundances of those nuclei for which a flux could be measured have been the same in five events. These results have supported the concept of a constant solar cosmic-ray composition for particles with the same charge-to-mass ratio. The ratio of protons to alpha particles in a solar cosmic-ray event is known to vary significantly, presumably because of the different charge-to-mass ratios of the two nuclear species. A study of this and other solar cosmic-ray events has led to the conclusion that this effect is due to the combined rigidity- and velocity-dependent nature of both the acceleration and the propagation of energetic solar particles. Since the most common iron isotope is Fe^{56}, the difference between its charge-to-mass ratio and that of oxygen should be considered.

In an effort to estimate the effect of the difference in charge-to-mass ratios, the proton-to-helium ratio can be considered as a guide. The charge-to-mass ratio of the hydrogen nucleus relative to that of $_2He^4$ is 2.00, while the charge-to-mass ratio of $_{26}Fe^{56}$ relative to that of $_2He^4$ is only 1.08. Consequently, the rigidity effects in propagation and acceleration should have a much smaller effect on the Fe^{56}/O^{16} value than on the proton/He^4 value. An analysis of the time history of this event and the degree of the rigidity dependence of the propagation suggest that at this point in the event the ratio of the flux of iron-group nuclei to the flux of He nuclei above 24.5 MeV nucleon^{-1} would be reduced relative to their ratio at the Sun, but by not more than 30 percent (and probably appreciably less). There is the additional possibility that there is bias in the acceleration process at a given energy per nucleon, or velocity, due to the different charge-to-mass ratio. Since we know of no good way of estimating the degree of this effect, if it exists at all, no attempt will be made to do so.

TABLE 1

ABUNDANCE RATIO OF IRON GROUP TO OXYGEN

Solar Cosmic Rays* (Same Velocity Interval)	Solar Photosphere†	Solar Corona‡	Galactic Cosmic Rays§ (Same Velocity Interval)
0.011 ± 0.003	0.008–0.010	0.008–0.12	0.19 ± 0.02

* Present work.

† Goldberg, Müller, and Aller (1960); Müller (1968); Lambert and Warner (1968).

‡ Pottasch (1964); Dupree and Goldberg (1967).

§ Waddington and Freier (1966); Webber, Ormes, and von Rosenvinge (1966); Comstock, Fan, and Simpson (1969).

The iron-group abundance relative to oxygen in the same energy per nucleon interval, as deduced above, is compared in Table 1 with the Fe/O value estimated for the Sun's photosphere, the Sun's corona, and galactic cosmic rays.

DISCUSSION

Considering the residual uncertainties in the abundance measurements and their interpretation, the measured relative abundance of the iron-group nuclei in the solar cosmic rays is easily consistent with the solar abundance. As mentioned in the previous section, earlier work has shown that there is good evidence to support the concept of a constant solar cosmic-ray composition from event to event in the nuclear-charge range from 2 to 20, insofar as measurements can be made. It also has been shown previously (e.g., Biswas *et al.* 1962; Durgaprasad *et al.* 1968) that this composition reflects that of the Sun's surface within the uncertainties of the measurements. The present work extends this conclusion to the iron group.

The abundance ratio of the iron group to oxygen for galactic cosmic rays is well established and is seen from Table 1 to be over an order of magnitude larger than the solar cosmic-ray ratio. This difference is an example of the general excess of heavy elements in the galactic cosmic rays relative to other—e.g., "universal," solar, and solar cosmic-ray—abundances. This feature is generally attributed to the uniqueness of the composition of the source of the galactic cosmic rays.

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